Chapter 5

Open loop systems

5.1 Description

Close loop systems are not efficient enough to satisfy the energy requirements of the area. Open loop systems are the next step. This is a more simple system in which water and heat are interchanged with the aquifer.

In open-loop GHE systems, a groundwater or surface water supply is used as a direct heat transfer medium, such that the water flows "one-way" through the building heat pump units. Once the water has refrigerated the machinery is discharged into the aquifer again.

![Figure 5.1: Open loop layout](image)

It is important to emphasize that there are a number of factors that are to be taken into consideration when dealing with this system:

**Mass balance** The amount of water extracted from the aquifer must be restored. This is the only way to avoid an impact to the aquifer.

**Clogging** The system will be used nearly 12 months a year. As a result, maintenance must be programmed to guarantee that the wells are operating
normally.

**Discharge quality** The discharge only consists of warm water. The area will suffer a progressive warming as a result of the implementation of the system. The water agency (ACA) should evaluate the consequences of this effect and decide whether it is dangerous or not for the aquifer.

**Location of the wells** Both wells should be located as near the heat exchangers as possible to reduce installation and operating costs. Avoiding by-pass of heat will be a crucial factor to decide on the final location of the wells since it would reduce the efficiency of the system.

### 5.2 Dipole

This first model will serve as a first approach to the understanding of the system. It may be useful to:

**Study different well configurations** It is important to bear in mind the existing relationship between the maximum abstraction rate without heat recirculation and the distance between both wells.

**Analyze the relevance of dispersion** As we did in the close loop systems, one of the main objectives of this thesis is to study the effects of dispersion in the heat transfer modelling.

Dissipated power is a function of the thermal gradient and the flow of water. If recirculation of warm water occurs, either less power will be dissipated or higher pumping will be needed to maintain the desired dissipation rates.

Considering all the economical and physical restrains is possible to analyze which configuration would be most useful for the future implementation of the system.

#### 5.2.1 Description

Two wells separated 25 m. are considered in an aquifer of dimensions 300*100*10. There is no need of multilayered analysis since the wells are considered as single points.

The injection well is placed downstream to make it more difficult to have thermal by-pass. The flux and transport parameters are the ones introduced in the second chapter in order to simulate the conditions of the Besos aquifer.

The time discretization consists of 3 years with a daily time step.

#### 5.2.2 Boundary and initial conditions

In this case, the boundary conditions are:

**Null water flux (Neumman condition)** North and South contours of the aquifer are assumed to have a null water flux condition because the gradient is parallel to them.

**Prescribed heads (Dirichlet condition)** Western and Eastern contours have a prescribed head simulating the natural gradient of the aquifer (0.15%).
5.2. DIPOLE

Figure 5.2: Temperature distribution at 120 days

**Prescribed flow (Neumann condition)** A flow of 65 m$^3$/d is prescribed in both wells. In the injection well, this is a positive value while in the pumping well it is negative.

The transport boundary conditions consist of several mass flow conditions. As it has been stated before, our transport conditions shall be called heat flow since we are dealing with heat as a solute. This boundary condition requires a concentration (in our case temperature) and the code calculate the heat flow as the product of the water flux of the zone and the input concentration. If water is leaving the system, the code considers the actual concentration in the balance instead of the prescribed one. In our case, this heat flow would be a sort of energy since we only need to take into account the specific heat of water to make the conversion.

**Heat flow (Robin/Neumann condition)** A heat flow with temperature of 25°C is prescribed in the injection well. Another heat flow with temperature of 16°C is prescribed in the pumping well. Since water is leaving the system at this point, the code will not take into account the prescribed temperature as explained before.

**Heat flow (Neumann condition)** Only Eastern and Western contours have transport boundary conditions. Northern and Southern countries have null flux boundary conditions and the resulting heat flow would be 0.

5.2.3 Results

No heat recirculation has occurred since the configuration of the wells guarantees it. Then, the dissipated power only depends on the water flow that is being pumped. The relationship between this parameters is given by the following equation:

$$ P = Q \cdot (\rho \cdot c)_w \cdot \Delta T $$  \hspace{1cm} (5.1)

Replacing each variable by its value the amount of power dissipated in this qualitative model is 28.3 kW.

The maximum extension of the heat plume generated by the injection is shown in this first picture.

1See Appendix 7.1 Boundary conditions
The injection ceases as the winter comes. The effect of advection is quite clear in the next picture, where the plume has travelled a certain distance. The velocity of the heat is governed by the retardation coefficient. In this case, the retardation coefficient is 2.5, that is, heat moves 2.5 times slower than water.

A second pulse in the systems starts, and the first plume is followed by a second one as depicts the third picture.
5.3 Regional model

In the end, a regional model of the delta created in the HG has been adapted and improved to simulate the implementation of GHE in the aquifer. The model represents the aquifer of the Besos delta.

![Besos delta extension](image)

**Figure 5.5: Besos delta extension**

5.3.1 Description

A number of existing and monitored wells have been represented in the model and have been used as possible locations of the injection and pumping wells. Several tests have been carried out in some of these wells and all the data collected provided the UPC with a good hydrogeological characterization of the area. This is the reason why these wells have been used but any other location may be possible.

In the first one, the wells were located as closest to the area of study as possible. The resulting distance between both was about 1600 m. The injection well was situated in Rambla Prim and the pumping well was placed in La
Maquinista. A second analysis was needed since the distance of 1600 m. was not feasible. Then, two other wells separated 650 m. were chosen.

Three different scenarios in terms of the dissipated power were determined by BR. Each of them represents the energy demand of a local area of La Sagrera during a whole year. Keeping in mind that the dissipated power depends on the temperature difference and the amount of water extracted from the aquifer, higher energy requirements will lead to higher extraction rates.

In the first analysis, the temperature difference between the water of the aquifer and the injection water was 9°C. In the second analysis, this difference was set at 5°C. Because of this, the annual amount of water mobilized would be higher in the second analysis:

Next figure depicts the evolution of the power demand vs. time in a year.

The first scenario only comprises the power demand of the future TGV railway station. The second scenario includes the magnificent building of the Triangulo Ferroviario. Finally, the third and most demanding scenario takes into account the energy requirements of the railway station and surroundings.
5.3. REGIONAL MODEL

### Table 5.1: Annual abstraction rates (H m$^3$)

<table>
<thead>
<tr>
<th>Scenario</th>
<th>$\Delta T$</th>
<th>$9^\circ C$</th>
<th>$5^\circ C$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 1</td>
<td>0.2</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>Scenario 2</td>
<td>0.6</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>Scenario 3</td>
<td>2.2</td>
<td>3.9</td>
<td></td>
</tr>
</tbody>
</table>

Figure 5.7: Annual power demand

#### 5.3.2 Boundary and initial conditions

The flux boundary conditions of the model are a mix of prescribed heads, prescribed flows and leakage conditions. All of them are listed below:

**Prescribed flow (Neumann condition)** All the contours of the aquifer apart from the sea have a prescribed flow boundary condition:

- In the North, a flow of 3000 m$^3$/d is entering the aquifer.
- A null flux BC is prescribed in both upper contours of the aquifer with Barcelona and Badalona.
- In the lower contours with Barcelona and Badalona, flows of 2140 and 3560 m$^3$/d are the inputs of the system.
- A number of active pumping wells have been taken into consideration as well. As a whole, they constitute an abstraction of 8072 m$^3$/d.

**Leakage condition (Robin condition)** A leakage condition consist of a prescribed head (reference) and a leakage coefficient. That is why it is also called mixed condition. The coefficient establishes the linear relationship between the flow and the heads difference.

$$Q = A.K \frac{\Delta h}{L}; \quad Q = \frac{A.K}{L}(h - H_{ext}); \quad Q = \alpha(h - H_{ext}); \quad \alpha = \frac{A.K}{L} (5.2)$$
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Units: \([\alpha] = \left[\frac{m^3}{d/m}\right]\)

Then, leakage conditions are then prescribed in the sea (south contour of the aquifer), the metro, the river and a parking lot.

As far as the transport boundary conditions is concerned, several heat flow conditions have been used. As it was detailed in former analysis, this BC requires a flow and a concentration (temperature in our case).

- A heat flow with a temperature of 25°C is prescribed in the injection well. While another with a temperature of 19°C is set in the pumping well.
- Every existing pumping, the contours (sea included) and the pumping well has a heat flow of 19°C associated. Since water is leaving the system, the code will not take into account the prescribed temperatures as explained in former sections.
- In the zones where a leakage or mixed condition was prescribed, a Robin condition (heat flow) to the transport problem with a temperature of 19°C was defined.

\footnote{See Appendix 7.1 Boundary conditions}
Since the recharge areas provide the aquifer with external water (mainly rain), the heat flow has an associated temperature of \(17^\circ C\) because we assume that water of the aquifer is slightly warmer than this one.

The initial conditions necessary for the solving of the problem are the following:

1. Water flux problem: An initial head of 0.1 m.

2. Transport problem: The aquifer is supposed to be initially at thermal equilibrium of \(16^\circ C\).

The time discretization of the first analysis was 5 years’ time with a daily time step. Despite the time step used in the second analysis was the same, the simulation time was extended to 20 years to evaluate long term efficiency of the system.
5.3.3 Results

Analysis 1 ($\Delta T=9^\circ C$)

![Piezometry at the peak of each year](image1)

Figure 5.9: Piezometry at the peak of each year (m.) (Scenario 1)

**Scenario 1** Taking a look at the piezometry of this scenario, it can be inferred that no great changes are caused by the heat exchangers. The existing pumpings create lower water table levels.

![Temperature distribution](image2)

Figure 5.10: Temperature distribution at the peak of the 3rd year (Scenario 1)

The heat plume generated by the injection rates of this scenario has an area of influence of approximately 500 m. of diameter. The maximum temperature reached in the surroundings of the well varies between 18-19$^\circ C$. 

Taking into consideration the local changes in the piezometry and the small dimension of the heat plume, it looks like this would be an acceptable scenario.
Scenario 3  In Scenario 3, an head of approximately 5-6 m. is originated in the injection point. Despite a red point indicating a piezometric level of 9 m. can be seen in the picture, it must be ignored. The reason of doing so is that the program calculates a high piezometric level because all the flow is injected in a single point with a very low computed area.

The heat plume generated by the injection rates of this scenario has an area of influence of approximately 750 m. of diameter. The maximum temperature reached in the surroundings of the well varies between 23-24°C. No heat recirculation occurs and the efficiency of the system remains at 100%.

In terms of heat impact to the aquifer, this is still a feasible scenario. Problems come up when dealing with head levels. That could turn out in filtration
Figure 5.14: Temperature distribution at the peak of the 5th year (Scenario 3)

problems, undesired water pressures and so on.
**Scenario 5** The picture is clear enough to show that this is not a feasible scenario. High drawdowns and head levels are caused in a big part of the aquifer. The scale of the measures has been kept to the same range to make the pictures more easy to compare. It must be noted that there are even higher values though but they have not been represented because this scenario is not possible at all.

The heat plume generated by the injection rates of this scenario has an area of influence of approximately 2000 m. of diameter. The maximum temperature reached in the surroundings of the well is 25°C. The shape of the heat plume is conditioned by the intensive pumping downstream. A certain heat recirculation occurs and as a result, it can be inferred that the efficiency of the system will decrease.
Figure 5.17: Temperature distribution at the peak of the 5th year (Scenario 5)

Figure 5.18: Temperature evolution (Scenario 5)

A temperature evolution of the temperature in the injection and pumping wells is depicted here. It is easy to notice the cycles in the injection. There is a first steep period in which the mixture between the groundwater and the injected water occurs. In contrast, there is a certain cooling of the water of the injection point due to the external recharge (cooler temperature). An increase in the temperature of the extracted water takes place around the day 1000. From there on, there is a trend to the increase of the pumped water temperature.
The steady state is not reached yet so a longer simulation would be needed to analyze this state. This is why in the second analysis, all the scenarios were calculated with a 20 years’ time simulation period.

As it was explained with the dipole model, the dissipated power is linearly dependant on the thermal difference of groundwater and pumped water. This is why if the abstraction rates are not changed, the dissipated power decreases with the increase of the abstracted water.
5.3. REGIONAL MODEL

Analysis 2(\(\Delta T=5^\circ C\))

![Piezometry at the peak of every year(Scenario 1)](image)

Figure 5.20: Piezometry at the peak of every year(Scenario 1)

**Scenario 1**  With the new distribution of the wells, scenario 1 does not imply a big impact in terms of important head levels. Pre-existing pumpings are still creating higher drawdowns.

![Temperature distribution at the peak of the 5th year(Scenario 1)](image)

Figure 5.21: Temperature distribution at the peak of the 5th year(Scenario 1)

At this stage, the heat plume generated by the injection rates of this scenario has an area of influence of approximately 2000 m. of diameter. The maximum temperature reached in the surroundings of the well varies between 21-22 °C. Even in this first scenario, some heat is recirculated in the pumping well.

Despite the change in the temperature of the pumping well is not extremely big, an increase in the temperature can be observed. The steady state is reached since the temperature remains approximately constant from the 11th year.

This figure depicts the effect of heat recirculation on the dissipated power as it has been explained in former sections.
Figure 5.22: Temperature distribution at the peak of the 10th year (Scenario 1)

Figure 5.23: Temperature distribution at the peak of the 20th year (Scenario 1)
Figure 5.24: Temperature evolution in the pumping well (Scenario 1)

Figure 5.25: Efficiency of the system (Scenario 1)
Scenario 3  There are levels of -4 m. in the pumping well and 6 m. in the injection one for scenario 3. This can be important since it may affect some infrastructures like the metro, buildings, etc.

The heat plume generated by the injection rates of this scenario has an area of influence of approximately 2000 m. of diameter. The maximum temperature reached in the surroundings of the well varies between 23-24°C.

To sum up, it must be stated that both in terms of head levels and heat plume dimension this scenario represents a kind of potential limit to the application of the system. The affections are important and some more detailed studies should be made in order to determine if lower values of power might be dissipated so as to reduce the impact on the aquifer.

This last figure shows the evolution of temperature of groundwater in the pumping well. The increase in temperature is approximately 1.5°C.
5.3. REGIONAL MODEL

Figure 5.27: Temperature distribution at the peak of the 5th year (Scenario 3)

Figure 5.28: Temperature distribution at the peak of the 10th year (Scenario 3)
Figure 5.29: Temperature distribution at the peak of the 20th year (Scenario 3)

Figure 5.30: Temperature evolution in the pumping well (Scenario 3)
5.3. REGIONAL MODEL

Figure 5.31: Piezometry at the peak of every year (Scenario 5)

**Scenario 5**  As it happened in scenario 5 of analysis 1, great changes occur in the piezometry of the aquifer. As a result, there is no way of a hypothetical implementation of this scenario.

Figure 5.32: Temperature distribution at the peak of the 5th year (Scenario 5)

In this scenario, a huge heat plume is generated. Too high abstraction rates are needed to satisfy these energy requirements.

Taking into account that the thermal difference between the injection water and groundwater is 5°C in analysis 2, it is unacceptable to have an increase of nearly 3°C in the pumping well.
Figure 5.33: Temperature distribution at the peak of the 10th year (Scenario 5)

Figure 5.34: Temperature distribution at the peak of the 20th year (Scenario 5)
Figure 5.35: Temperature evolution in the pumping well (Scenario 5)